DEVELOPMENT OF A SMALL-PERIOD, LINEAR, WIGGLER MAGNET FOR A UBITRON

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Final Report on Contract Number N00014-86-C-2421

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ABSTRACT

A double-sided wiggler magnet with period on the order of 1 cm has been optimized and improved in design. Good peak to peak uniformity along with tapered entrance conditions has been achieved. Peak magnetic field in the range 1-3 kG is easily realized so long as the gap separating the two sides of the magnet is smaller than about one half of a wiggler period. Such a restriction on gap separation implies that a ubitron utilizing a rectangular waveguide circuit could not be made to operate at its fundamental frequency with electron energy below 100 keV. Investigation of a third harmonic ubitron utilizing a linear wiggler is recommended to achieve operation at electron energy in the range 30-60 keV.

I. INTRODUCTION

The objective of the present study was to develop a double-sided, linear wiggler magnet with period $\ell_w \leq 10$mm, and peak amplitude of the peak wiggler field on the axis of symmetry 1-3 kG. It was intended that such a wiggler be used in a millimeter-wave ubitron using a rectangular waveguide circuit and with electron energy in the range 30 keV to 60 keV. Millimeter wave ubitrons in the past had typically utilized electron beams with kinetic energy > 100 keV, and the feasibility of operation at much lower voltage was by no means obvious.

In section II below, development of the small period wiggler magnet is described. Fabrication to achieve $\ell_w \leq 10$mm and 1 kG < B_w < 3 kG was indeed feasible. Also, techniques were developed to improve the peak to peak uniformity of the magnetic field and to taper the entrance conditions into the wiggler magnet. However, operation with fields > 1 kG forces one to use a gap separation between the two sides of the magnet that is small; viz., $\delta \lesssim \ell_w/2$.

In section III, the effect of the small gap dimension in limiting the range of ubitron operation is discussed. In particular, calculations for even the lowest order ubitron mode, TE_{01}, show that the requirement of having $\delta < \ell_w/2$ which sets a

lower band in the cutoff frequency, is incompatible with having electron energy as low as 60 keV. In light of this finding it was concluded that no calculation of gain for a 30-60 keV, millimeter-wave ubitron could be made. Instead, further studies are recommended into the feasibility of harmonic ubitron operation.

II. WIGGLER MAGNET DESIGN AND PERFORMANCE

The basic design of the wiggler electromagnet is described in reference 1 and 2. In early versions of the wiggler, a conducting sheet of copper runs through a stack of insulated ferromagnetic laminations in alternating directions, and the copper sheet and laminations are squeezed together to form a rigid structure. A current is passed through the copper sheet to produce a periodic magnetic field and two such structures can be used to produce a bilateral wiggler producing a linear, transverse, periodic magnetic field. In latter versions, the wiggler is made of a machined block of copper into which iron laminations are inserted to controlled depths; this type of fabrication allowed for adjustment of the magnetic field strength in each half period.

The magnetic fields in a number of experimental wiggler magnets of this type were measured, and the relative thickness of the copper and the iron as well as the height of the copper foil were optimized. Transverse magnetic fields were measured with a Hall effect probe and Gaussmeter. The wiggler magnet was energized by an a.c. 60 Hz power supply capable of providing large currents. Previous studies[2] have demonstrated that saturation in the ferromagnetic laminations is significantly reduced for a.c. powered electromagnets compared with identical d.c. powered electromagnets. For a repetively pulsed FEL, a.c. magnet excitation at a frequency keyed to the pulse repetition rate may be acceptable.

The transverse magnetic field in the region near the center of the air-gap between the electromagnet which form the wiggler, may be approximated by

$$B_w(y,z) = \frac{4\mu_0 I}{\pi h}\frac{\sin(k_w h/2)}{\sinh(k_w \delta/2)}\sin(k_w z)\cosh(k_w y) \tag{1}$$

where h is the copper thickness, $k_w = 2\pi/\ell_w$, and the co-ordinate system is shown in Figure 1. The peak magnetic field amplitude is clearly dependent on the ratio of air-gap short dimension, δ, to the magnet period, ℓ_w.

Measurements of the transverse fields have confirmed Equation (1). As can be seen from Figure 2, fields approaching 0.2 T may be obtained for $\ell_w = 9.5$ mm and $\delta = 4.2$ mm ($\delta/\ell_w = 0.44$). Peak field uniformity of about $\pm$ 5% has been achieved as shown in Figure 3: the field on the first peak was adjusted to be $\sim$ 50% of the interior peak fields to provide an appropriate electron beam entrance condition.

III. ACCESSIBLE FREQUENCIES FOR UBITRON OPERATION

As indicated above, to obtain undulator fields with sufficient strength for ubitron interaction in short period planar undulators, one must utilize a narrow gap δ between the magnet pole pieces. In particular, our studies have found the a gap-to-period ratio $\delta/\ell_w \leq 0.5$ is necessary to obtain peak wiggler fields of several kilogauss.

As a result of this restriction on undulator magnet separation, the interaction region will be bounded by thin, closely spaced conducting walls. Hence a calculation of the FEL operating frequency must account for waveguide dispersion

$$\omega^2 = \omega_{c0}^2 + k_z^2 c^2, \tag{2}$$

as well as phase resonance

$$\omega \approx (k_w + k_z)\beta_z c, \tag{3}$$

where $\beta_z = v_z/c$ is the normalized axial velocity. The lowest order rectangular vacuum waveguide mode which has a resonant FEL interaction with the sheet electron beam is the TE_{01} mode. For FEL operation with this mode, Equations (2) and (3) can be simultaneously solved for the resonant frequencies

$$\omega = \beta_z \gamma_z^2 k_w c \ \{1 \pm [\beta_z^2 - (\frac{1}{2\rho\gamma_z})^2]^{1/2}\}, \tag{4}$$

where $\gamma_z = [1 - \beta_z^2]^{-1/2}$ is the relativistic axial energy parameters. $\rho = b_{rf}/\ell_w$ is the ratio of the narrow transverse waveguide dimension b_{rf} to the wiggler period, and $b_r f$ is related to the magnet gap spacing via the waveguide wall thickness t_{rf}:

$$b_{rf} = \delta - 2t_{rf}. \tag{5}$$

Equations (2) and (3) are plotted in Figure 4(a) and b_{rf} is pictured in Figure 4(b). Collective effects have not been included in Equation (4).

Substituting Equation (5) into Equation (4) yields the plot of accessible resonant FEL frequencies versus beam voltage shown in Figure 5. The region above the solid line represents points for which $\delta > \ell_w/2$ (i.e., weak wiggler fields for a short period wiggler). Points below the solid line are accessible with the right combination of wiggler period and beam voltage, as indicated by the broken lines. Thus, it appears unlikely that ubitrons operating at the fundamental frequency can be developed to operate with electron energy < 60 keV.

IV. SUMMARY AND RECOMMENDATIONS

The linear wiggler study has been quite successful in developing a wiggler configuration with good peak to peak uniformity and adjustable entrance conditions. Moreover, the wiggler design is easy to fabricate and inexpensive.

However, it does not appear feasible to design a ubitron operating at its fundamental frequency with an electron beam energy in the range 30–60 keV. One way to achieve such low voltage ubitron operation might be to operate at harmonies of the ubitron frequency. For a given signal frequency, harmonic operation implies larger wiggler period and larger gap separation with a corresponding decrease in the electron beam energy required for achieving ubitron resonance condition. Recent

analyses[3,4] have shown that a ubitron with a planar wiggler has strong interaction at odd harmonics, and a 3rd harmonic ubitron study is recommended.

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Figure Captions

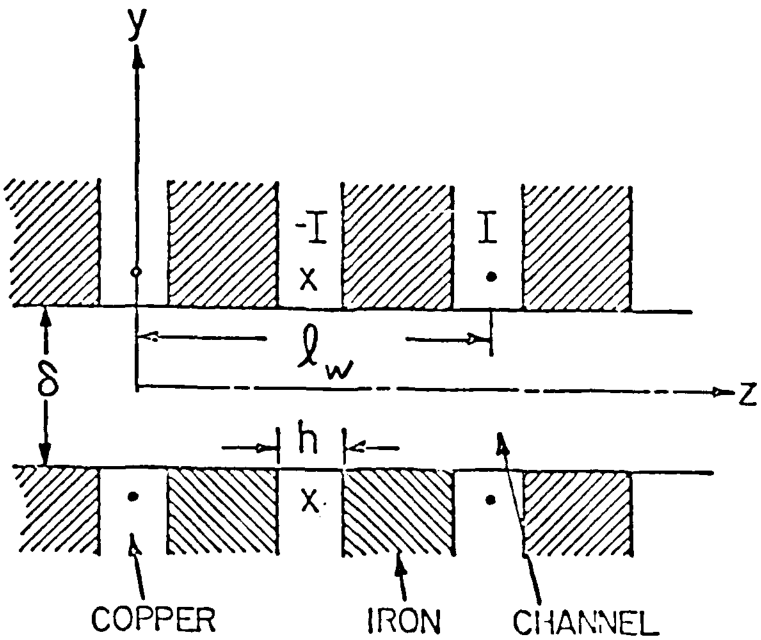
1. Side view of the wiggler magnet sliced along the center line. I is total current through both halves of the magnet.

2. Peak magnetic field vs. the rms value of the magnet current, I: ($\ell_w = 9.5mm$, $h = 3.2mm$, height of each side of the wiggler in the y direction was 1.5 cm).

3. Magnitude of the peak magnetic field vs. axial position, z. (a) $|B_{max}|$ vs z with equal insertion depth for each segment of iron. (b) $|B_{max}|$ vs z with insertion depths adjusted to minimize variation in B_{max} for half period numbers 2 through 19, and to make B_{max} for half period numbers 1 and 20 equal to approximately 0.5 times the central value of B_{max}.

4. (a) Dispersion curves relevant to ubitron operation. (b) Ubitron waveguide geometry showing relationship of waveguide dimension to gap separation and waveguide wall thickness.

5. Accessible frequencies for short-period wiggler ubitron operation. For this figure, a value of waveguide wall thickness, $t_{rf} = 0.25mm$ was assumed.



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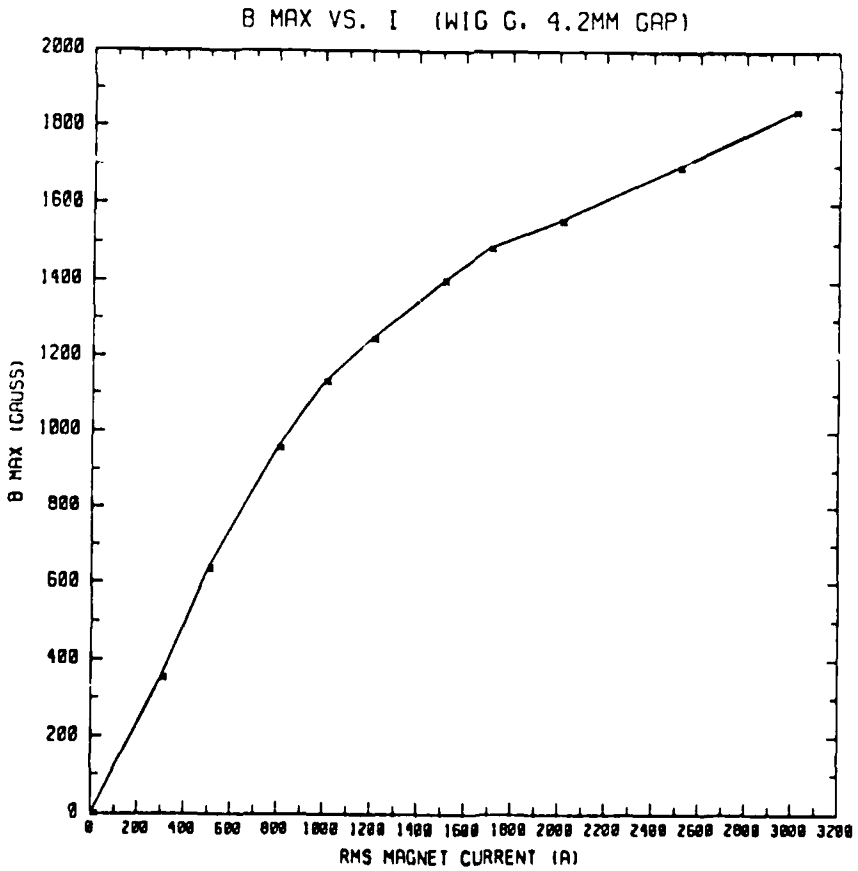

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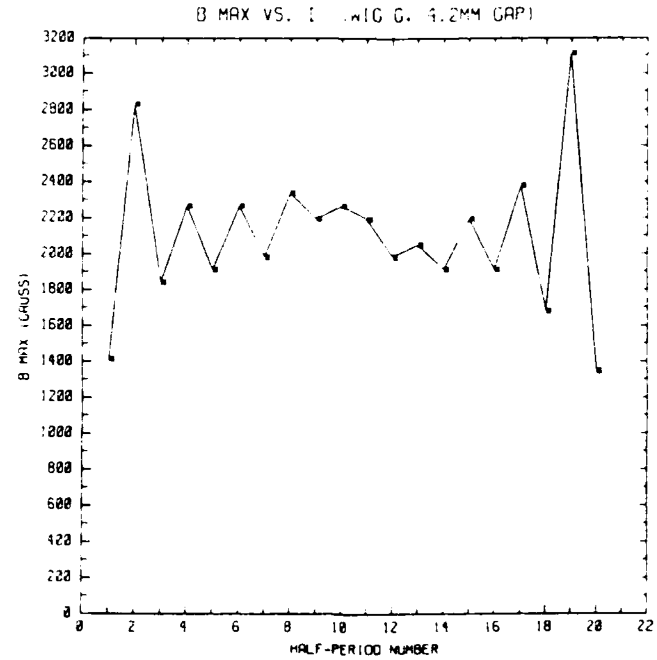

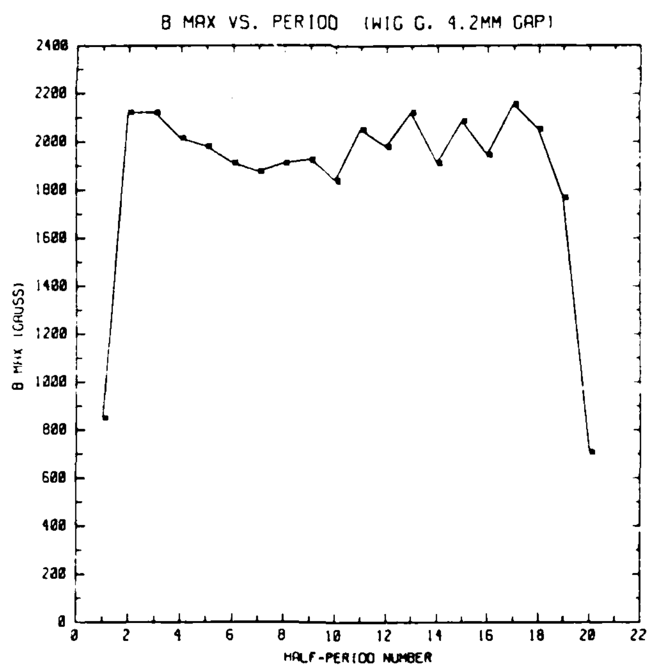

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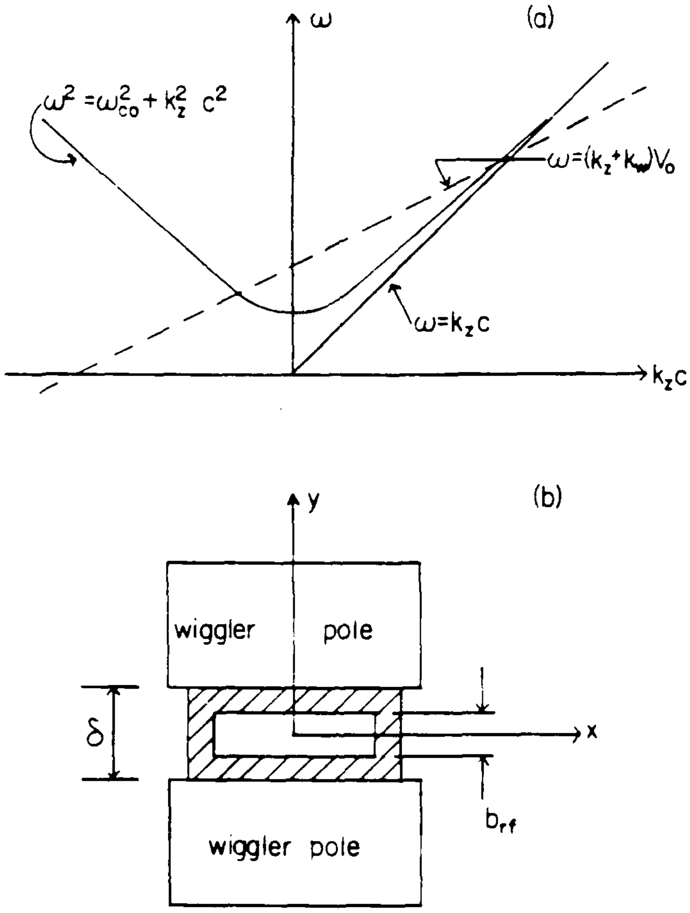

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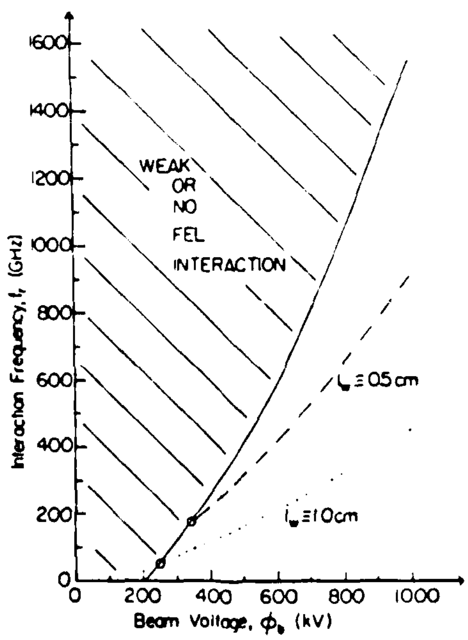

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